Carbon Looping Energy Assessment and Retrofit

Chemical and Biomolecular Engineering

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CLEAR

BALTIMORE-WASHINGTON INDUSTRIAL CORRIDOR

Why KOH-Ca DAC?

Liquid KOH–Ca looping was selected as a representative DAC system because it is among the most developed and well-documented air-capture pathways. Its calcium looping section is analogous to calcination chemistry used in the cement industry, giving it a clearer scale-up basis than other emerging DAC concepts.

Energy Bottleneck

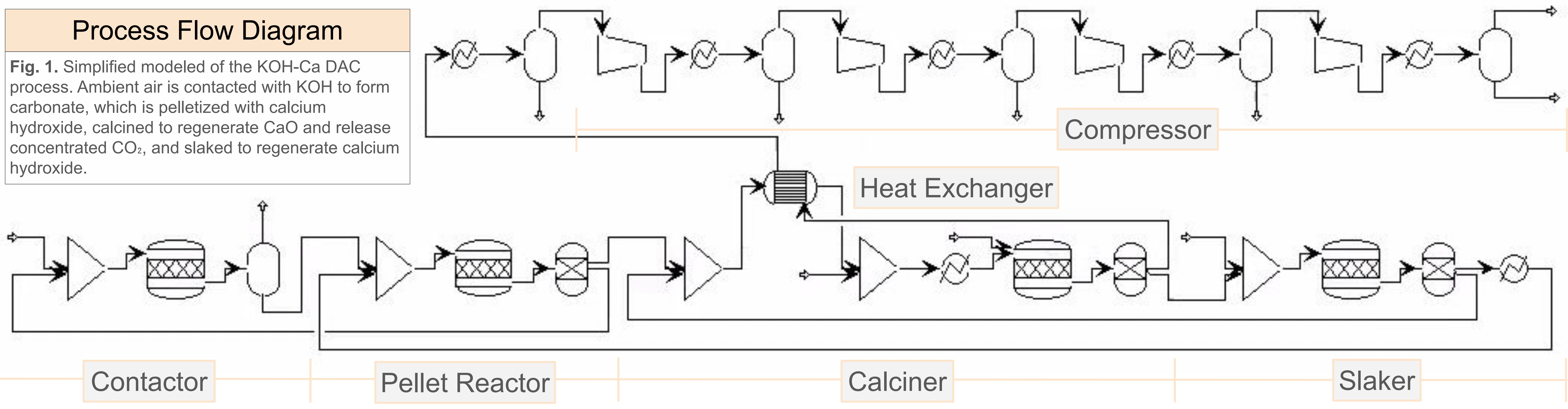
Although this produces concentrated CO₂, regeneration requires a high-temperature calciner and substantial natural-gas input. The system is both a materials problem, through solvent and sorbent regeneration, and an energy one, through the heat required to release CO₂ and close the loop.

Integration Strategy

This project evaluates whether the energy burden can be reduced through direct heat recovery, heat pumping, and concentrating solar thermal heating. These strategies are tested on the KOH–Ca base case, but the framework can be extended to other DAC materials, regeneration schemes, and future CO₂ utilization pathways such as sustainable aviation fuel.

Process Flow Diagram

Fig. 1. Simplified modeled of the KOH-Ca DAC process. Ambient air is contacted with KOH to form carbonate, which is pelletized with calcium hydroxide, calcined to regenerate CaO and release concentrated CO₂, and slaked to regenerate calcium hydroxide.



Metric		Ref	Aspen
CO_2 [Mt/yr]	captured	0.92	0.86
	delivered	1.4 (0.971 CO_2)	1.2 (0.956 CO_2)
Calciner duty [MW]		186	478
HX recovery [MW]		-	40
Low-quality heat		-	530

Table 1. Significant material and energy balances for the reference design and Aspen model. Calciner duty differences likely reflect simplified calciner modeling, including less detailed treatment of combustion heat management and recovery.

Heat Exchanger Network (Fig. 2)

A heat exchanger network was evaluated before heat pumps or external heating because it uses energy already present in the process. Pinch analysis through composite curves identified which hot streams could offset cold-stream demand, most significantly for the calciner feed. The screening showed that most available heat was too low temperature to heat the calciner feed. The only feasible source was the calciner CO_2 effluent, which could **transfer 40 MW** and **raise the temperature to 343 °C** toward the 650 °C target.

The recoverable heat is limited by its temperature quality. A heat exchanger reduces, but does not eliminate, natural-gas demand. Calciner feed preheating can be partially offset, but the calciner's high-temperature duty cannot.

Heat Pump (Fig. 3)

Heat pumps were evaluated using the Python model originally developed for the DIB column, where heat pumping successfully upgraded condenser heat for reuse in the reboiler. For DAC, the heat remaining after heat exchanger integration was too low-temperature to directly heat the calciner feed or the calciner itself, despite having a sufficient quantity. The model was extended to determine whether the low-quality heat could be upgraded. The most relevant sources included the partially cooled calciner CO₂ effluent and slaker recycle streams, which retained heat but not at temperatures high enough for direct heat exchange.

At a moderate sink temperature, the heat pump could upgrade 24.03 MWth of source heat and deliver 43.42 MWth using 19.39 MWe of compressor work. This heat could be **useful for future CO₂ utilization steps**, but it cannot heat the remaning calciner feed to the 650 °C target or the 900 °C calciner duty. As temperature lift increases, COP decreases; vapor-compression **heat pumping is impractical for the calciner's high-temperature heating**.

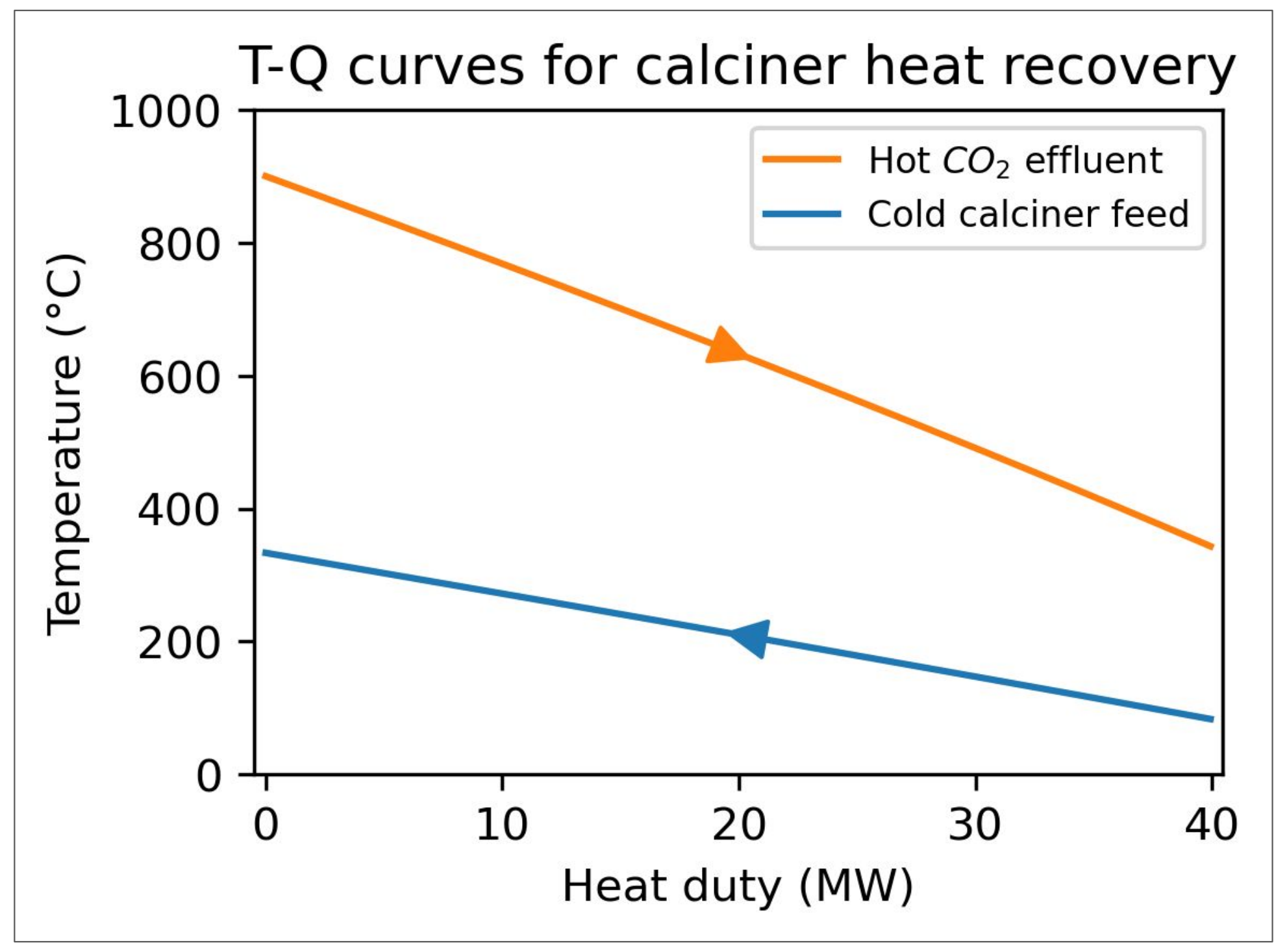


Fig. 2. T-Q curve confirming feasible heat exchange between the calciner CO_2 effluent and calciner feed. Arrowheads show the direction of temperature change for each stream.

Concentrating Solar Thermal (Fig. 4)

Concentrating solar thermal was evaluated as a future external heat source for reducing natural-gas use in the calciner. Unlike solar PV, it concentrates direct normal irradiance onto a receiver, producing high-temperature heat; falling-particle receivers are being developed for calciner-compatible temperatures. Because the calciner operates continuously but DNI varies by location, season, and weather, the model used four seasonal windows to compare average heat offset and daily variability. The Baltimore-Washington Industrial Corridor was the primary case, but DAC removes atmospheric CO₂ rather than fixed point-source emissions, so higher-DNI regions such as the Arizona Sun Corridor can also be considered.

Assuming high-temperature solar thermal calciners are successfully scaled by 2050, a 1000-acre aperture could offset meaningful fractions of the 478 MWth calciner duty, especially in Arizona. However, seasonal variability and cloudy-day losses show that solar thermal cannot reliably replace natural gas alone. Continuous operation would require hybrid heating or thermal storage.

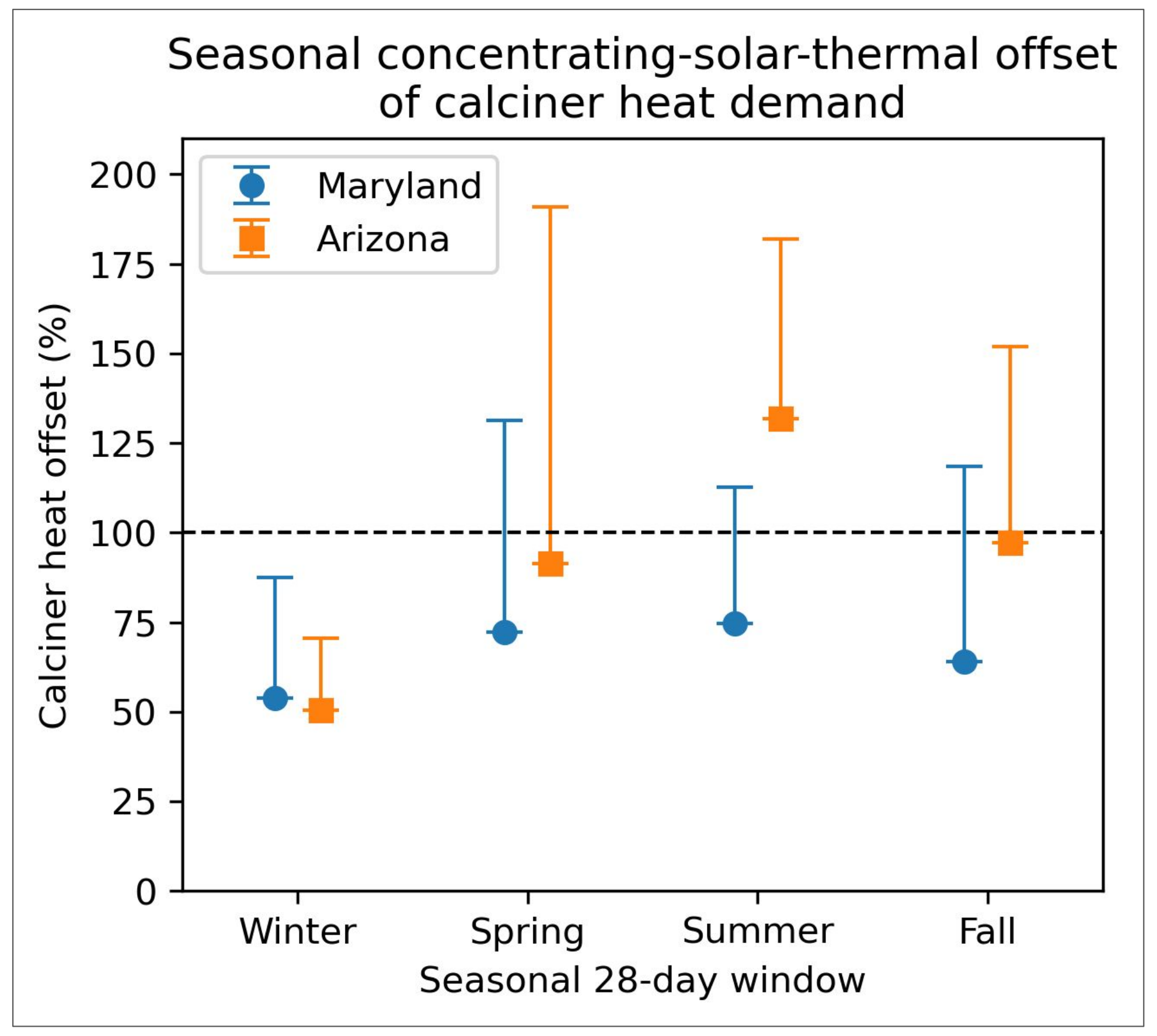
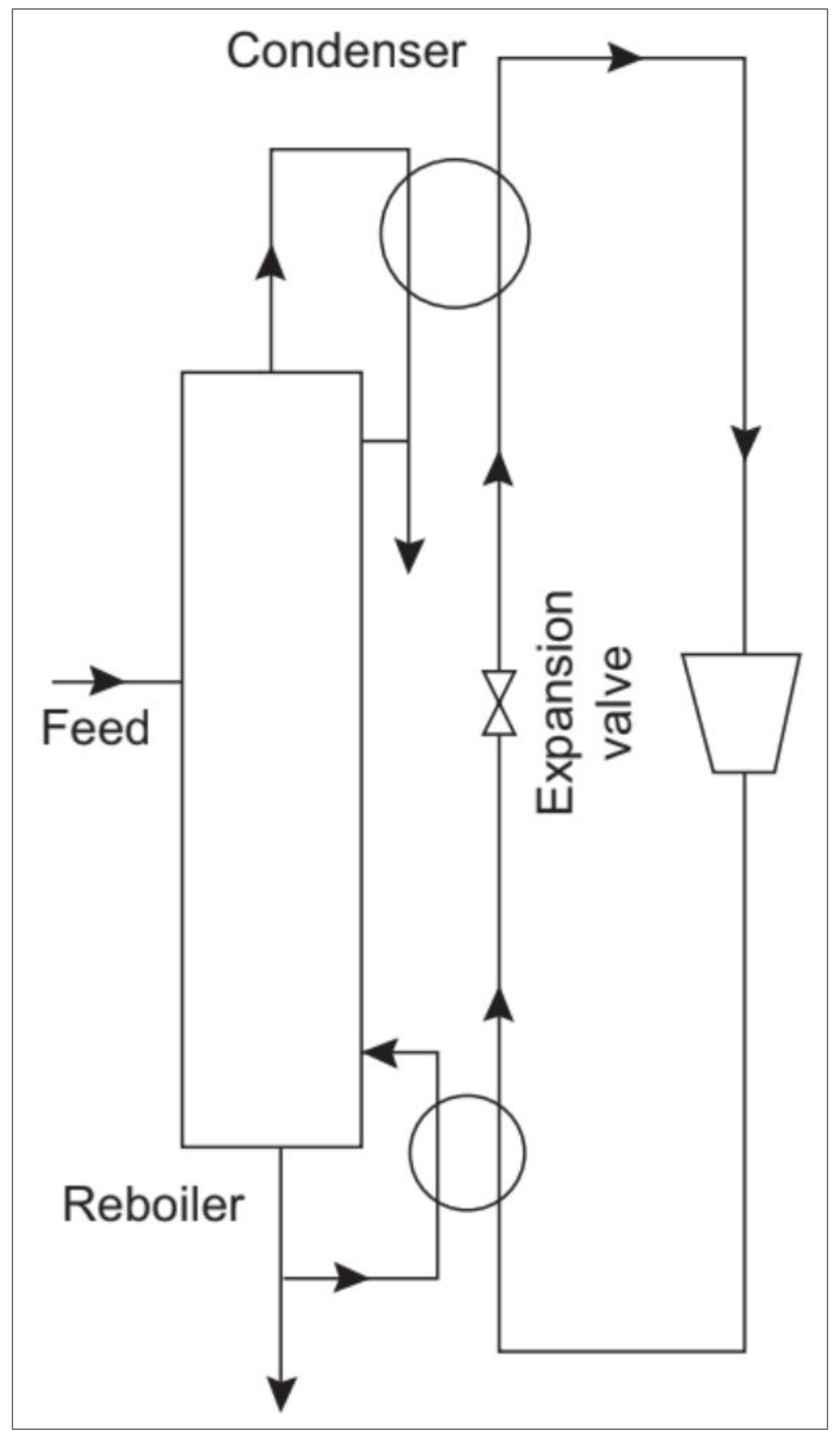


Fig. 4. Average daily calciner heat offset for four 28-day windows centered on the solstices and equinoxes. Maryland and Arizona cases use regional solar geometry and seasonal DNI. Points show average offset, and upper error bars show the maximum daily offset within each window; lower error bars are omitted because because fully cloudy days can produce near-zero DNI. Calciner demand is 478 MW at 900 °C, aperture is 1000 acres, and solar-to-calciner efficiency is assumed to be 0.45.

Fig. 3. Heat pump configuration used as the basis for the Python model. Arrowheads show the refrigerant cycle. Heat is absorbed from the low-temperature source in the condenser, upgraded through the compressor, and released to the high-temperature sink in the reboiler.



Techno-Economic Analysis

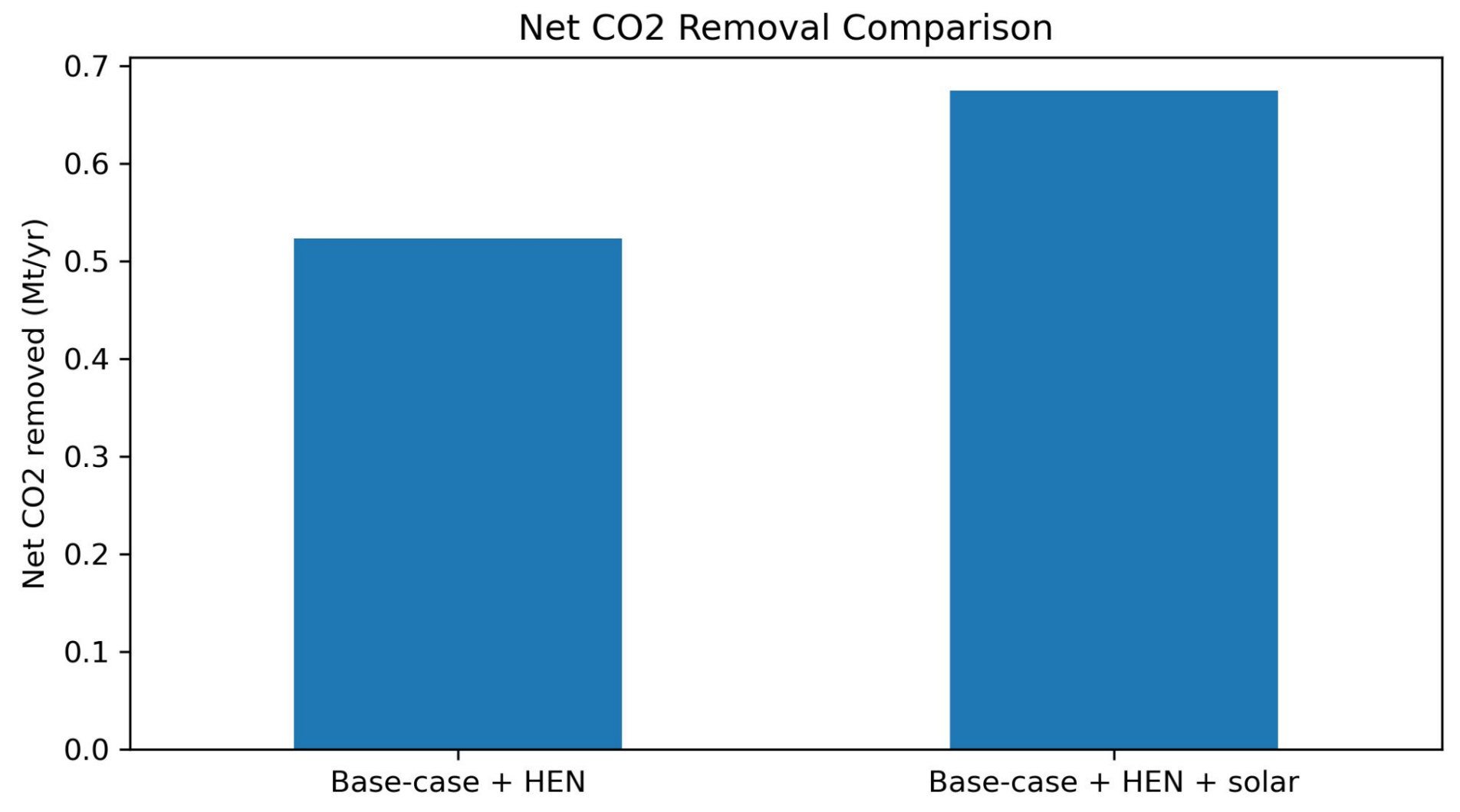


Fig. 5. Purchased energy demand(GJ/t-CO_2) for each model based on ASPEN results.

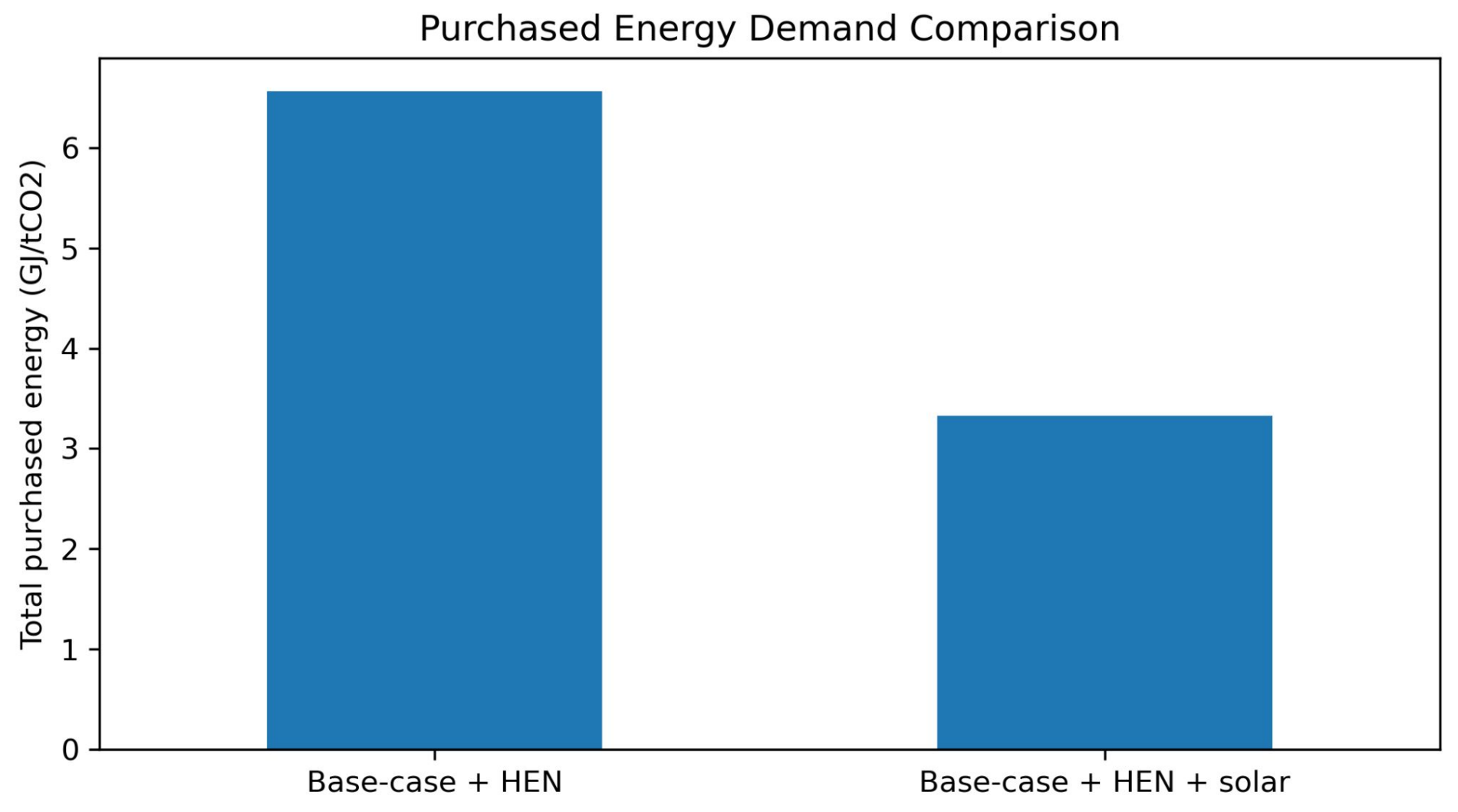


Fig. 6. Net CO_2 removed(Mt/yr) comparison based on ASPEN results

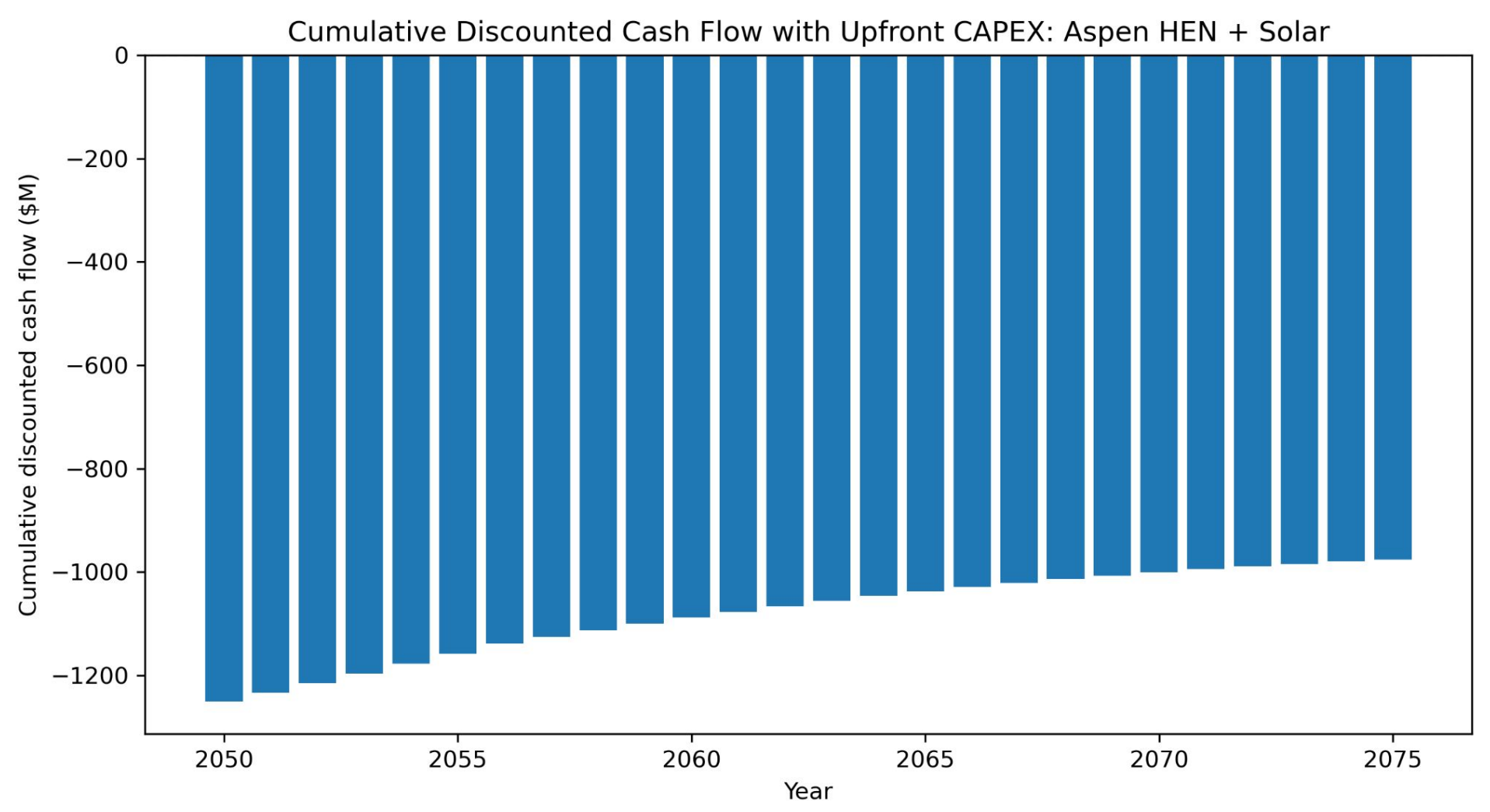


Fig. 7. Cumulative discounted cash flow projection for the Aspen HEN + solar L-DAC system

Conclusions

- Heat integration and solar thermal reduce energy demand, but do not make KOH–Ca DAC broadly feasible under current conditions.
- DAC remains conditional on earlier decarbonization pathways and is most defensible for residual emissions or hard-to-abate utilization needs, such as sustainable aviation fuel.
- Continued R&D is needed for the DAC process and enabling technologies, including high-temperature calciners, solar receivers, and thermal storage.
- Future work should extend the model downstream to CO₂ utilization and apply this integration framework to other DAC materials and regeneration schemes.

[1] Keith, D. W.; Holmes, G.; St. Angelo, D.; Heidel, K. Joule 2018, 2, 1573–1594. [2] Ulrich, G. D.; Vasudevan, P. T. Chem. Eng. 2006, 66–69. [3] U.S. EPA. GHGRP Emission Factors, 2023. [4] U.S. EIA. Natural Gas Prices, 2025. [5] NREL. Solar Capacity Factors, 2023. [6] LoopNet. Dundalk Industrial Site Listing, 2026.